BOILER PERFORMANCE OPTIMIZATION USING FUZZY LOGIC CONTROLLER

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Abstract: This paper considers an approach to design a controller used for the air-to-fuel ratio (AFR) optimization in the combustion process of a power plant boiler. The optimization of the AFR will reduce the excess air level and improve the combustion efficiency in the boiler system. The combustion improvement indicates boiler operating cost savings. The fuzzy logic controller, which is a method of a rule-based decision making based on human knowledge, was developed for the combustion process and its performance and effectiveness were then compared with the classical PI controller. Simulation results demonstrate how the designed fuzzy logic controller performs well to the optimization of the AFR in the combustion process and applying the controller to the combustion process will result in significant operating annual cost savings in the boiler operation.

Keywords : fuzzy control, optimization, boilers, combustion process, PI controller

1. INTRODUCTION

Boilers have been used in many industrial activities such as in power plant and for processing purposes (Ordys et al., 1994). In a combined heat and power plant, a boiler has an important role that is as a part which produces steam. The energy to generate steam is produced by a heat, as a result of the combustion process in the boiler part. Furnace, where air and fuel are combined and burned, produce heat and flue gases to the risers part of the boiler. The mixture of steam and water will go to the steam drum and the steam will be transferred into other part of the boilers.

Optimization of the boiler performances has been an interesting subject of investigation for many years (Liptak, 1999). One of the optimization goals is to reduce the operating cost savings of a boiler. The most common energy and cost saving opportunity in a boiler is in combustion improvement. An alternative way for the combustion improvement is by reducing the excess air and the oxygen percentage level from the combustion process which can optimize the boiler performances. Combustion improvement is indicated by the increase of the combustion efficiency in the combustion process of a boiler.

The boiler combustion control system in order to optimize the boiler performances has been explored and developed in recent years (Dukelow, 2001). The design controller method and technique is varied from the conventional controller, like PI controller, up to the intelligent based controller such as Fuzzy Logic Controller. In a complex system such as combustion system of a boiler, the need to design and implement a suitable controller which has a fast response of time and one that can control the nonlinear behavior of a complex system has become a focal point in the development of the boiler control.

Meanwhile, the fuzzy systems have been a focus for interest of many researchers in various scientific and engineering areas (Jang *et al,* 1997). The number and variety of applications of fuzzy logic has been increasing, ranging from consumer products and industrial process control to medical instrumentation, information systems, and decision analysis. Fuzzy sets and fuzzy logic were developed as a means for representing, manipulating, and utilizing uncertain information and to provide a framework for handling uncertainties and imprecision in real-world applications. Fuzzy logic is complementary technology in the design of intelligent systems.

In this paper, a development of a fuzzy logic controller for a combustion process will be introduced. Air-to-fuel ratio become the control variable for the combustion improvement and the basis for the calculation of the operating cost savings. The effectiveness and the performance of the proposed intelligent controller will be demonstrated by off-line simulation of the combustion process. Performance comparison was also made if the boiler combustion process was controlled using the conventional PI controller. A cost saving improvement in boiler operation will be shown by using the proposed intelligent control method. The simulation studies of the proposed boiler control scheme was conducted by means of real-time control software developed using graphical-based programming language LabVIEW (LabVIEW, 1998)

2. BOILER COMBUSTION SYSTEM

A simplified schematic diagram of a typical boiler representing the selected range is illustrated in Fig 1., showing major components of such boilers (Ordys et al., 1994) :

- Combustion chamber where the fuel is burnt to release heat.
- Drum which contains water and steam.
- Waterwalls (the risers) where water is heated.
- Superheater that heats up the steam until it reaches the superheat temperature.
- Reheater that reheats steam from other parts of the boiler.
- Economizer used to preheat the water and absorbed heat from the flue gas.

2.1 Combustion Process

Combustion is the rapid oxidation of fuel in a mixture of fuel and air with heat produced and carried by the mass of flue gas generated. Combustion is accomplished by mixing fuel and air at elevated temperature. Steam is generated from the burning of variety of fuels. The basic combustion process and its elements are shown in Fig 2.

In actual practice, gas-, oil-, coal-burning and other systems do not perform a perfect job of mixing fuel and air even under the best achievable conditions of turbulence. To assure a complete combustion, additional combustion air is furnished so that every molecule of the fuel can easily find the proper number of oxygen molecules to complete the combustion.

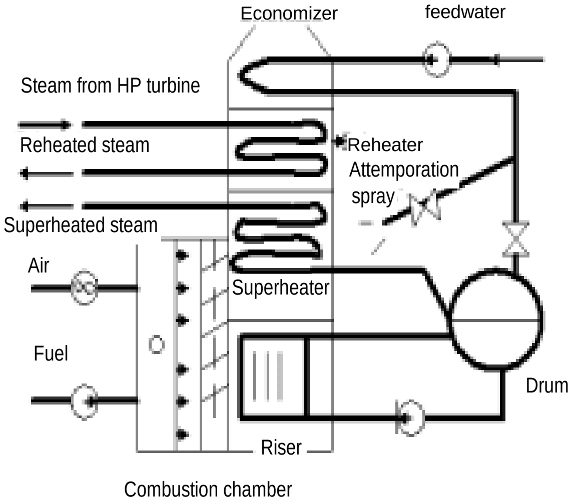


Fig 1. Boiler schematic diagram

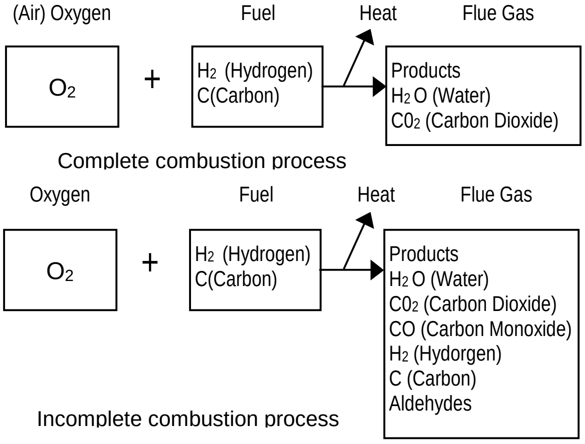


Fig 2. Basic combustion process

2.2 Excess air and oxygen percentage

The additional amount of combustion air that is furnished to complete the combustion process is called excess air. Having this necessary excess air means that some of the oxygen will not be used and will leave the boiler in the flue gas. The basic equation for the excess air in (Liptak, 1999) will be applied, which is given in the following form

$$y = 100(w_A + \gamma_A w_G - w_F R_S)\frac{1}{w_F R_S} \qquad (1)$$

where y is the excess air , w_A is the airflow, w_F is the fuel flow, w_G is the exhaust gas flow, γ_A is the content of fresh air in exhaust from gas turbine, and R_S is the air-to-fuel ratio.

Some of the oxygen that leaves the boiler as a flue gas basically will determine the percentage of excess air level. Since the amount of excess air is already known, based on equation (1), the calculation of the oxygen percentage will be reversed after the excess air is being calculated. The formula for the excess air based from the oxygen percentage is as follows

$$\text{Excess Air (\%)} = K\left[\frac{21}{21-\%oxygen}-1\right]\text{x}\,100 \qquad (2)$$

where K is equal to 0.9, 0.94 and 0.97 for gas, oil and coal, respectively. The formula is based on "dry basis" percentage of oxygen. Table 1 shows the required excess air at full capacity for various fuels used in the combustion process.

Table 1. Excess air required at full capacity

Fuel	% Oxygen in flue gas	% Excess air, minimum
Natural gas	1.5 to 3	7 – 15
Fuel Oil	0.6 to 3	3 – 15
Coal	4.0 to 6.5	25 – 40

2.3 Combustion Efficiency

Along with the process, the flue gas will exit the boiler through the stack with an elevated temperature. This means that not all the heat is being transferred to warm up the water in the riser's part. The flue gas temperature indicates that the heat will leave the boiler as one of the losses occurs in the combustion process. Combustion efficiency is a measure of how effectively the heat content of fuel, or heat produced from the combustion process, is transferred into the usable heat. The measurement of the combustion efficiency is affected by the fuel supply, excess air level or the oxygen percentage, type of fuel used, combustion air and flue gas temperature.

2.4 Air-to-Fuel Ratio Optimization

Air-to-fuel ratio (AFR) is the ratio between a certain amounts of air which reacts to certain amount of fuels. Efficient boiler operations require the continuous matching of fuel and air flows while maintaining a slight air excess. The air and fuel flow meters are scaled down so they both need to be at the same percentage to give the right AFR ratio.

As one of the variables that affecting the excess air level in the combustion process, as shown in eq. (1), maintaining and optimizing the proper AFR will reduce the excess air level. The reduction of the excess air level will result in a combustion improvement of a boiler since excess air is one of the losses that occurs in a boiler. Combustion improvement is indicated by the increase of the combustion efficiency. This will also lead to a saving of a boiler cost production eventually. The operating cost savings is affected by the combustion efficiency and also the steam cost production of a boiler.

4. FUZZY LOGIC CONTROLLER

Fuzzy logic is a method of rule-based decision making used for expert and control system that emulates the rule-of-thumb process thought used by human beings. Fuzzy logic describes a system with linguistic variables which is human understandable. The basis of fuzzy logic is the fuzzy set theory which allows for partial membership, or a degree of membership, which might be any value along the continuum of 0 and 1. Fuzzy set is characterized by a membership function, which specifically defines degrees of membership based on a property. Another variable that characterizes fuzzy logic controller is the fuzzy rule-based. In fuzzy rule-based the knowledge of an expert in a field of applications is expressed and is described as follows

"IF x_1 is A_1, x_2 is A_2, …, x_n is A_n, THEN y is B" (3)

where "x_1 is A_1, x_2 is A_2, …, x_n is A_n" is the given condition; "y is B" is called the consequences or conclusions; 'x_1, x_2 …, x_n and y' is the fuzzy variables; while A and B is the fuzzy values.

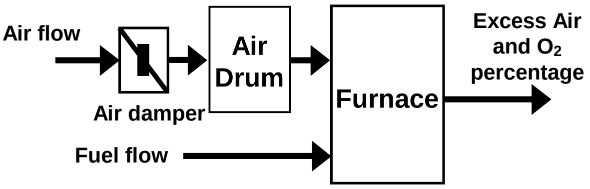


Fig 3. Combustion process model

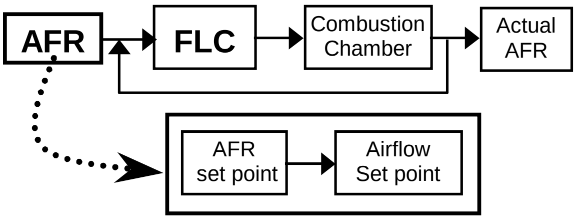


Fig 4. FLC block diagram

Fuzzy logic controller will be used to control and optimize the proper air-to-fuel ratio (AFR) in the combustion process. The manipulated variable in the combustion process is the air damper. For the simplification of the fuzzy logic, it will be assumed that the AFR will first determine the airflow set point in the air drum and after the actual air flow reaches the airflow set point then the process will be continued. The control action taken by the fuzzy logic controller is to control the air damper. The combustion process model used in fuzzy logic controller (FLC) is shown in Fig. 3. and the fuzzy logic controller block diagram is shown in Fig. 4. The inference system used for the fuzzy logic controller is the Mamdani Inference System.

There are two inputs for the controller, which is the error and the rate of change of error, and one output which is the air damper. The error is the differences between the actual AFR with the AFR set point. The membership function that is used for the input variable are the singleton, triangular and trapezoidal function, and the membership function for the output variable is triangular and trapezoidal function.

The universal discourse for the error input variable and the rate of change of error is divided into five fuzzy sets, that is, NB (negative big), Z (zero), PS (positive small), and PB (positive big). While the output variable, the air damper, is divided into three fuzzy sets, which is, NB (negative big), NS (negative small) and Z (zero). These fuzzy sets are determined through observation with trial and error process.

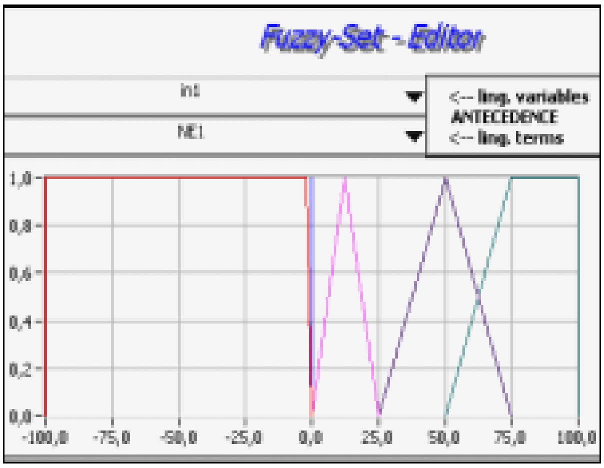


Fig 5. Error and rate of change of error input membership function

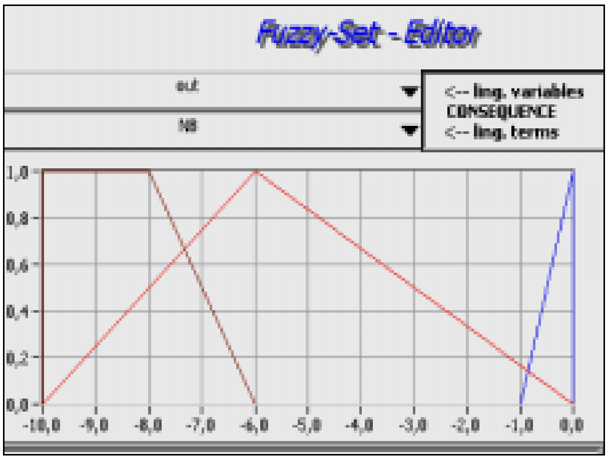
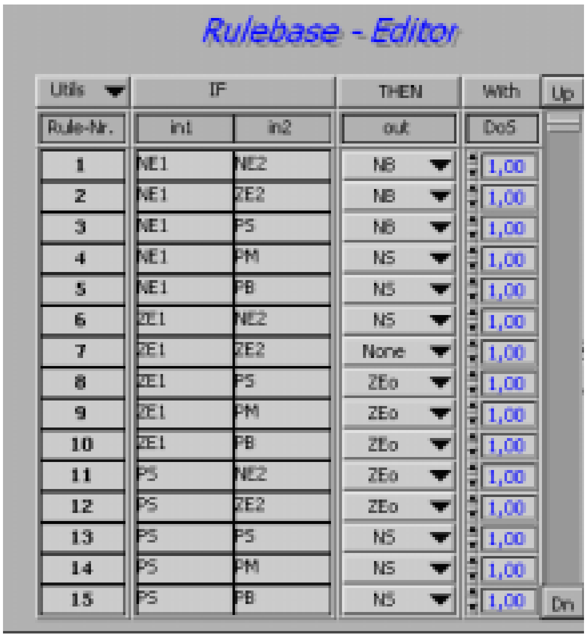


Fig 6. Output variable membership function

The input range for error and the rate of change of airflow error variables is limited at -100 to +100, while the output variable, which is the analog value for the air damper, is being limited from -10 to zero. The determination of the controller range region is also based on the observation of the combustion chamber characteristics. The input boundary is determined based on the minimum and maximum error that occurs in the process, while the output variable is determined to give the best result that is faster response and high stability of the process.

The input, output and rule-base design used in the fuzzy logic controller resulting from the LabVIEW software are shown in Fig. 5, 6 and 7. There are 25 rule-bases that have been formulated for the control action. Fig. 7 illustrates some of the rule-bases design used in the fuzzy logic controller. The rule-bases were determined based-on trial and error process. Moreover, the rule-bases represent the air damper characteristics for the combustion process.



Rule-Nr.	IF in1	IF in2	THEN out	With DoS
1	NE1	NE2	NB	1,00
2	NE1	ZE2	NB	1,00
3	NE1	PS	NB	1,00
4	NE1	PM	NS	1,00
5	NE1	PB	NS	1,00
6	ZE1	NE2	NS	1,00
7	ZE1	ZE2	None	1,00
8	ZE1	PS	ZEo	1,00
9	ZE1	PM	ZEo	1,00
10	ZE1	PB	ZEo	1,00
11	PS	NE2	ZEo	1,00
12	PS	ZE2	ZEo	1,00
13	PS	PS	NS	1,00
14	PS	PM	NS	1,00
15	PS	PB	NS	1,00

Fig 7. Fuzzy rule sets

5. SIMULATION RESULTS AND EVALUATION

The configuration of the combustion process parameters used in the experiment is shown in Fig. 8.

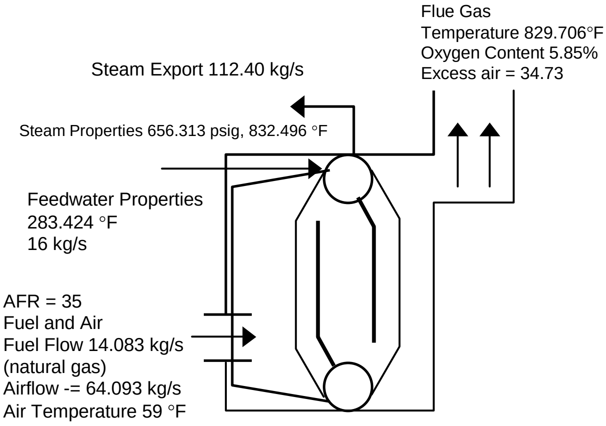


Fig. 8. Boiler parameters

Fig. 9 shows the result of control using off-line simulation. As comparison, a control action based on the conventional PI controller method was also conducted in the experiment. Fig. 10 shows the PI controller block diagram used to control the air-to-fuel ratio (AFR). The procedure consists of estimating the best parameter for the K_P and T_i based on the response of the system. There were six experiment conducted to determine the best PI controller parameters. Table 2 displays the parameter of the six experiments along with the settling time and root mean square error (RMSE), defined as

$$RMSE = \sqrt{\left(\sum_{k=1}^{N} e^2(k)\right) / N} \qquad (4)$$

where e(.) denotes the error at time k and N is the total data taken.

Based on the information and using an empirical formula, PI controller parameters were determined, which yields setting parameters for PI controller, $K_P = 10$ and $T_i = 20$ sec. These parameters are the best parameters after conducting six experiments. The plant response using these controller parameters is illustrated in Fig. 11.

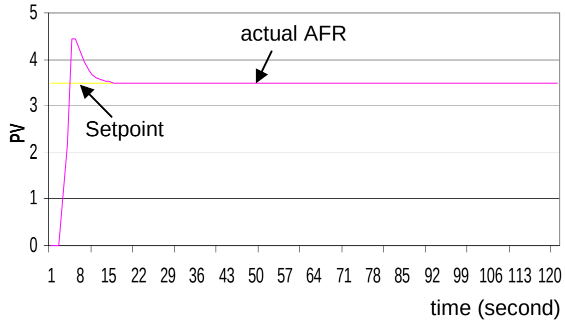


Fig 9. Plant response using fuzzy logic controller

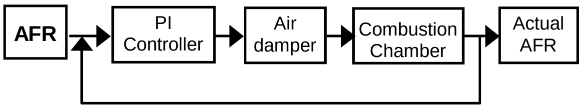


Fig 10. Block diagram using PI Controller

Table 2. PI Controller data experiment

Experiment	K_P	T_i	Settling Time (second)	RMSE
1	2	4	178	0.5105
2	2	8	64	0.4692
3	5	8	73	0.4671
4	10	8	89	0.4663
5	**10**	**20**	**46**	**0.4899**
6	10	25	69	0.4938

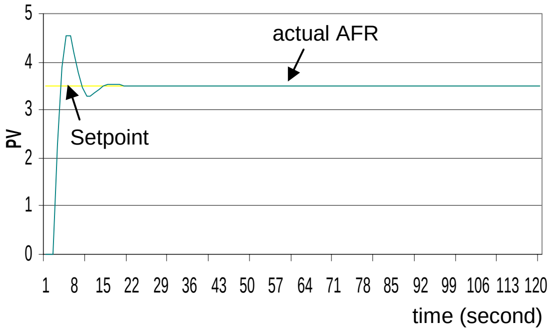


Fig 11. Plant response using PI controller

As performance measure, the transient response, the overshoot and the RMSE values were all used in all simulation studies. Fig. 12 illustrates the plant response, compared between PI controller and fuzzy logic controller, while Table 3 shows the results of comparison between PI controller and fuzzy logic controller. As can be observed, better performances are shown using the fuzzy logic controller to the conventional PI controller. In Fig. 12, it is also shown that fuzzy controller has faster anticipation in any changes in the process variable.

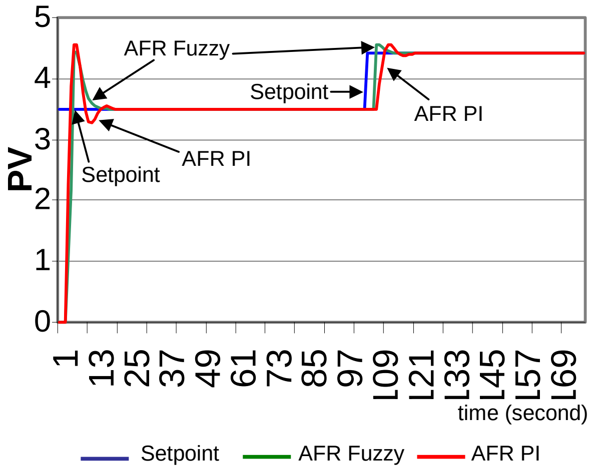


Fig 12. Comparison of plant responses

Table 3. Fuzzy and PI controller comparison

	Fuzzy Logic Controller	PI controller ($K_P = 10$; $T_i = 20$)
Settling time	22 s	46 s
Transient Response	No. oscillation	Small oscillation
RMSE	0.6238	0.49389
Overshoot	26.74%	30.03%

6. COST SAVINGS CALCULATION

As have been explained previously, combustion improvement indicates an operating cost savings in the boiler system. An optimized AFR will reduce the excess air level and also the oxygen percentage from the combustion process and it will lead to an increment in the combustion efficiency.

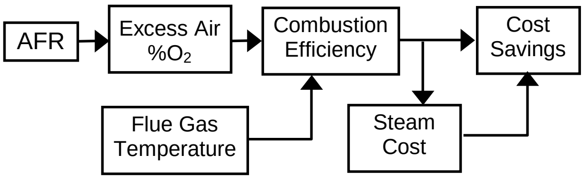


Fig. 13. The cost savings calculation diagram

The operating cost savings is calculated based on fuzzy logic controller and the boiler parameters shown in Fig. 8. The steam cost calculation will be brought first since it is needed for the cost savings calculation. As comparison, a cost savings calculation based on PI controller will also be exposed in the experiment. Fig. 13. shows the cost savings calculation diagram used in the experiment.
Steam cost is the cost production of the fuel to generate steam ($/ 1000 lbs of steam) (DOE, 2000). This cost is dependent upon fuel type, unit fuel cost, boiler efficiency, feedwater temperature, and steam

pressure. The steam cost calculation provides a good first approximation for the cost of generating steam and serves as a tracking device to allow for boiler performance monitoring. The steam cost calculation is shown in the following equation.

Steam Cost = fuel price x energy required to produce one pound of sat steam x $\frac{1}{\eta}$ (5)

The data for the steam cost calculation is shown as follows :

- The energy required to generate one pound of steam [CNN Money, 2004] = 948.64 (Btu / lb)
- The natural gas price [CNN Money, 2004] = US$ 5.588 per MM Btu.

Steam Cost = US$5.588/ MM Btu x 948.64(Btu / lb) x $\frac{100}{71.06}$ = US$7.743/ 1000 lbs

The general formula for counting the savings associated with optimized boiler combustion efficiency is as follows (Russell and Tubiolo, 2002) :

Cost Savings = Fuel Consumption x $\left(1-\frac{E_1}{E_2}\right)$ x steam cost (6)

where E_1 is the old combustion efficiency, E_2 is the new combustion efficiency, fuel consumption is fuel used in boiler (annually), and steam cost is the fuel cost to generate steam in a boiler ($/1000 lbs of steam).

The data for the cost saving calculation are as follow:

- $E_1 = \eta_1 = 71.06$,
- $E_2 = \eta_2 = 74.64$,
- Fuel consumption = 14.083 kg/s = 6.394 lbs/s = 201641184 lbs/yr
- Steam cost = US$7.743/ 1000 lbs

The cost savings based on the above data is :

Cost savings = 6.394 lbs/s x $1-\left(\frac{71.06\%}{74.64\%}\right)$ x US$7.743/ 1000 lbs
= 201641184 lbs/yr x 0.047x US$7.743/1000lbs
= US$74,885.872 annually

The operating cost savings comparison between fuzzy logic and PI controller is shown in Table 4. The AFR for the PI controller is taken when fuzzy logic has reached the AFR set point, or based on fuzzy logic controller settling time, the optimized AFR is also taken in the same manner. The cost savings from the experiment is observed only from controlling the air-to-fuel ratio (AFR) from the combustion process. Other part of the boiler system can be optimized as well, such as reducing the flue gas temperature exiting the boiler, steam pressure, etc. By optimizing other part of the boiler system the operating cost savings will be much more significant then only optimizing one variable, which has been discussed in this paper.

Table 4. Fuzzy and PI controller cost savings

	Fuzzy Controller	**PI Controller**
Air-to-fuel ratio (AFR)	3.500	3.491
Optimized AFR	4.410	4.401
Excess Air	34.73	35.07
New excess air	6.93	7.17
% oxygen	5.85	5.89
New % oxygen	1.50	1.55
η_1	71.06	71.05
η_2	74.64	73.92
Steam cost (/1000lbs)	US$ 7.743	US$ 7.743
Cost savings (per year)	**US$ 74,885.872**	**US$ 60,407.737**

7. CONCLUSIONS

An approach to design a fuzzy logic controller used for the air-to-fuel ratio (AFR) optimization in the combustion process of a power plant boiler has been presented. The optimization of the AFR will reduce the excess air level and improve the combustion efficiency in the boiler system. The combustion improvement indicates a boiler operating cost savings. It has been shown that, based on the optimized AFR, an annual cost savings of $US 74,885.872 will be achieved. Better performance for the combustion process was also shown from the results using fuzzy logic controller compared to the conventional PI controller.

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